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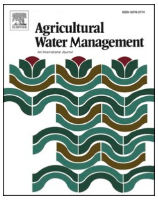

Rainfed spring canola yield response to changing heat and water stress in the Canadian Prairie region

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ABSTRACT

Canola is a significant crop in Canadian agriculture and the economy. However, Canada's average temperatures have risen rapidly over the past eight decades, changing temperature patterns and water availability for canola production. This study aims to explore the impacts of air temperature and soil water availability on spring canola production from 2025 to 2050. Accordingly, this study introduces DSSAT calibration and simulation of the current hybrid InVigor®L340PC, integrating the Shared Socioeconomic Pathways. Leveraging DSSAT-Pythia, gridded simulations capture spatial variability in water and temperature stress interactions, driven by a large ensemble of climate models. The analysis reveals how precipitation and temperature changes jointly influence spring canola development. Yield projections under these conditions provide critical insights into the future viability of rainfed spring canola and inform adaptation strategies for growers and policymakers. Findings demonstrate negative impacts on exclusively rainfed spring canola production in the Canadian Prairie Region under diverse climate scenarios from 2025 to 2050. The main canola growing ecozone (Aspen Parkland) is expected to have higher air temperatures and lower soil water content if greenhouse gas emissions keep rising. An average increase of 1.5°C in air temperature and 0.025 in the water stress factor indices may result in annual yield reductions of 203 ± 4.3 and 121 ± 13.6 kg ha^{-1}, in Lake Manitoba Plain and Aspen Parkland ecoregions, respectively. Given that future canola production is expected to continue in the same ecoregions it is recommended that adaptation and mitigation strategies are developed and adopted to improve canola production conditions in these ecoregions.

1. Introduction

Canola is cultivated mainly in Canada, the United States, Europe, China, and India (Raman et al., 2019). Canola was cultivated in more than 8.9 million hectares in Canada in 2024, accounting for approximately 10 % of Canada's total cropland. Approximately 80 % of Canada's cropland is in Alberta, Manitoba and Saskatchewan, the Prairie Provinces. Together, they cultivate practically 100 % of canola production in Canada (Statistics Canada, 2025a). Canola production is important to the Canadian economy with total exports of canola seed for oil extraction from Canada raising more than CAN$5.7 billion in 2024 (calendar year) (Statistics Canada, 2025b). However, water deficits and extreme temperatures may affect its production, directly impacting the vegetable oil, feedstock, and biofuel industries.

The water available in agricultural soils is crucial for plant growth and vitality. Water requirements and use for canola change according to

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the environmental conditions and soil moisture availability. The minimum amount of water that canola requires for vegetative growth (from germination to the reproductive stage), which lasts approximately 40–60 days, is 100 mm (Canola Council of Canada, 2024; McKenzie and Woods, 2011). This requirement will increase in warm and dry conditions due to higher moisture consumption for transpiration. Canola water requirements increase at least three times during the reproduction stage. Under ideal conditions in the Canadian Prairie Region, spring canola requires 400–480 mm of water during the growing season (May to September). Canola average water needs in Alberta start at 0.1 mm day^{-1} after emergence and peak during flowering and beginning of pod development, reaching 7 mm day^{-1} (McKenzie and Woods, 2011). Spring canola has a tap root system, reaching an average of 140 cm deep at maturity. Because secondary roots grow from the tap root, more than 50 % of soil water extraction occurs within 60 cm of soil depth (Canola Council of Canada, 2024; Liyanage et al., 2022). A dry soil environment implies greater crop losses (Wu et al., 2021a) as soil moisture stress impacts leaf and stem growth (McKenzie and Woods, 2011). These dry conditions reduce plant growth and development, affecting branching and crop yield capacity, seed weight, and oil yield. Further, a severe and prolonged water deficit will cause faster plant senescence and death (McKenzie and Woods, 2011; Ghafoor et al., 2021), causing irreversible loss in production if it happens early in the season.

In addition to affecting rainfall extremes (Moustakis et al., 2021), temperature extremes can critically affect plant productivity and health. Each crop has an optimum air temperature range which maximizes growth and reproduction. For canola development, the base temperature is 5℃, the optimum temperature is 26℃, and the maximum temperature is 40℃ (Hamza et al., 2023). Canola development is estimated by measuring Growing Degree Days (GDD) by subtracting canola's base temperature of 5℃ from the average daily temperature over time (Canola Council of Canada, 2024). A change in length of GDD due to air temperature rises and variability alters plant physiology, causing it to stop developing to protect itself, as extreme temperatures are lethal (Hekstra, 1986; Luo, 2011). A rise of 1.5℃ was found to lower oilseed production by approximately 11.5 %, causing an estimated yield loss of approximately 7.5 % with a 1℃ rise in air temperature (Wu et al., 2021a). The consequences become even more severe when multiple extreme events coincide, compounding detrimental effects on crop production and grain yield (Lesk et al., 2021, 2022).

Accurate crop models are crucial to simulate and explore the impacts of climate change on the future of crop production and plan for climate-smart farms under various individual and compound extreme conditions (Asgari et al., 2022a). Crop models have diverse applicability and complexity (Gavasso-Rita et al., 2024) that can vary from well established semi-empirical models, e.g. AquaCrop (FAO, 2023), statistical and machine learning models (Slater et al., 2022) to fully mechanistic models (Buckley Paules et al., 2025). The Decision Support System for Agrotechnology Transfer (DSSAT) has shown accurate results when simulating canola phenology and yield (Asgari et al., 2022b; Xu et al., 2021) and is widely used. It stands out from other crop models as an important decision-making system for stakeholders (Sarkar, 2009; You et al., 2024). DSSAT combines weather, soil, genetics, management, pests and economics to model and analyze cropping systems of more than 40 crops to provide crop growth, development, and yield results, essential for strategic plans. DSSAT computes the daily soil water balance and evapotranspiration daily for all crops, including canola (Hoogenboom et al., 2019a).

Previous studies used DSSAT to analyze the effects of climate change on crop production with Representative Concentration Pathways from the fifth phase of the Coupled Model Intercomparison Project (Dias et al., 2016; Gunawat et al., 2022; Li et al., 2015). The Sixth phase has been released with more complex scenarios, the Shared Socioeconomic Pathways (SSPs). The SSPs are narratives describing societal development, including economic, educational, technological advancements, and environmental challenges (O'Neill et al., 2016, 2017). Accurately predicting spring canola production under future climate conditions is essential for understanding both the beneficial and adverse impacts of climate change on crop productivity, and for guiding the development of effective adaptation and mitigation strategies. In particular, the interaction between water availability and temperature plays a critical role in shaping yield outcomes. Understanding these dynamics enables producers to anticipate climate-driven changes, optimize management practices, and enhance productivity while minimizing environmental impacts (Ejaz et al., 2023).

This study aims to demonstrate the combined impacts of air temperature and soil water content availability on rainfed spring canola productivity in the Canadian Prairie region and ecoregions. Hence, this study introduces several novel contributions to the field. First, it includes the calibration and simulation of the current hybrid cultivar InvigorL340PC®, a widely adopted hybrid cultivar not previously simulated in DSSAT. Second, it integrates climate projections from SSP1–2.6 (Sustainability), SSP2–4.5 (Middle of the Road), SSP3–7.0 (Regional Rivalry), and SSP5–8.5 (Fossil-Fueled Development) to simulate future conditions from 2025 to 2050 (O'Neill et al., 2016, 2017). Third, the study utilizes the DSSAT-Pythia framework to conduct gridded simulations across the Canadian Prairie Region, enabling spatially explicit analysis of climate impacts. Fourth, it includes mechanistic analysis of water and temperature stress interactions, which emerge from the ensemble of climate projections. Finally, it projects spring canola yields under the combined effects of water stress and high temperature stress, offering insights into the most detrimental conditions for rainfed canola production and the potential future of canola cultivation across distinct ecoregions. This will support producer decision-making and broader sustainability planning by addressing the real-world challenges of climate change and canola production in a critical agricultural zone.

2. Methods

2.1. Study region

The study site is the Canadian Prairie Region, an area of great interest for spring canola production in Canada (Agriculture and Agri-Food Canada, 2024). The Prairie Region is in the southern areas of Alberta, Manitoba, and Saskatchewan in the western part of the country (Fig. 1). There are more than 90 thousand farms across Alberta, Manitoba, and Saskatchewan that represent almost 50 % of the total farms in Canada. Approximately 18 thousand farms cultivate oilseed (excluding soybeans) in the Prairie Provinces (Statistics Canada, 2025a). Saskatchewan has the largest harvested area of canola in Canada, totalling over 4.8 million ha, representing more than 50 % of Canada's total harvested area. Alberta has the second-largest harvested area of canola (just over 2.5 million ha, and Manitoba has the third-largest harvested area of over 1.3 million ha (Statistics Canada, 2025a).

The Canadian Prairie Region is divided into seven ecoregions — Aspen Parkland, Cypress Upland, Fescue Grassland, Lake Manitoba Plain, Mixed Grassland, Moist Mixed Grassland, and Southwest Manitoba Uplands (Fig. 1). Aspen Parkland is a transitional zone between the boreal forest and the grasslands. Most of this area experiences cold, long winters and short, warm summers. This ecoregion has one of the most productive agricultural lands due to the fertility of black soils. The Cypress Upland has a lower precipitation range than Aspen Parkland but similar temperature conditions. This ecoregion has good conditions for raising free-range livestock, and crop production is favoured only on less steep slopes. The Fescue Grassland benefits from the chinook wind occurrence that causes a dramatic temperature change, warming this whole ecoregion rapidly and resulting in mild winters and warm summers. Average precipitation ranges from 400 to 450 mm annually. Comparatively, Lake Manitoba Plain is the most humid ecoregion of the Canadian Prairie with cereals the most produced crops. The region experiences 700 mm mean annual precipitation and mean summer

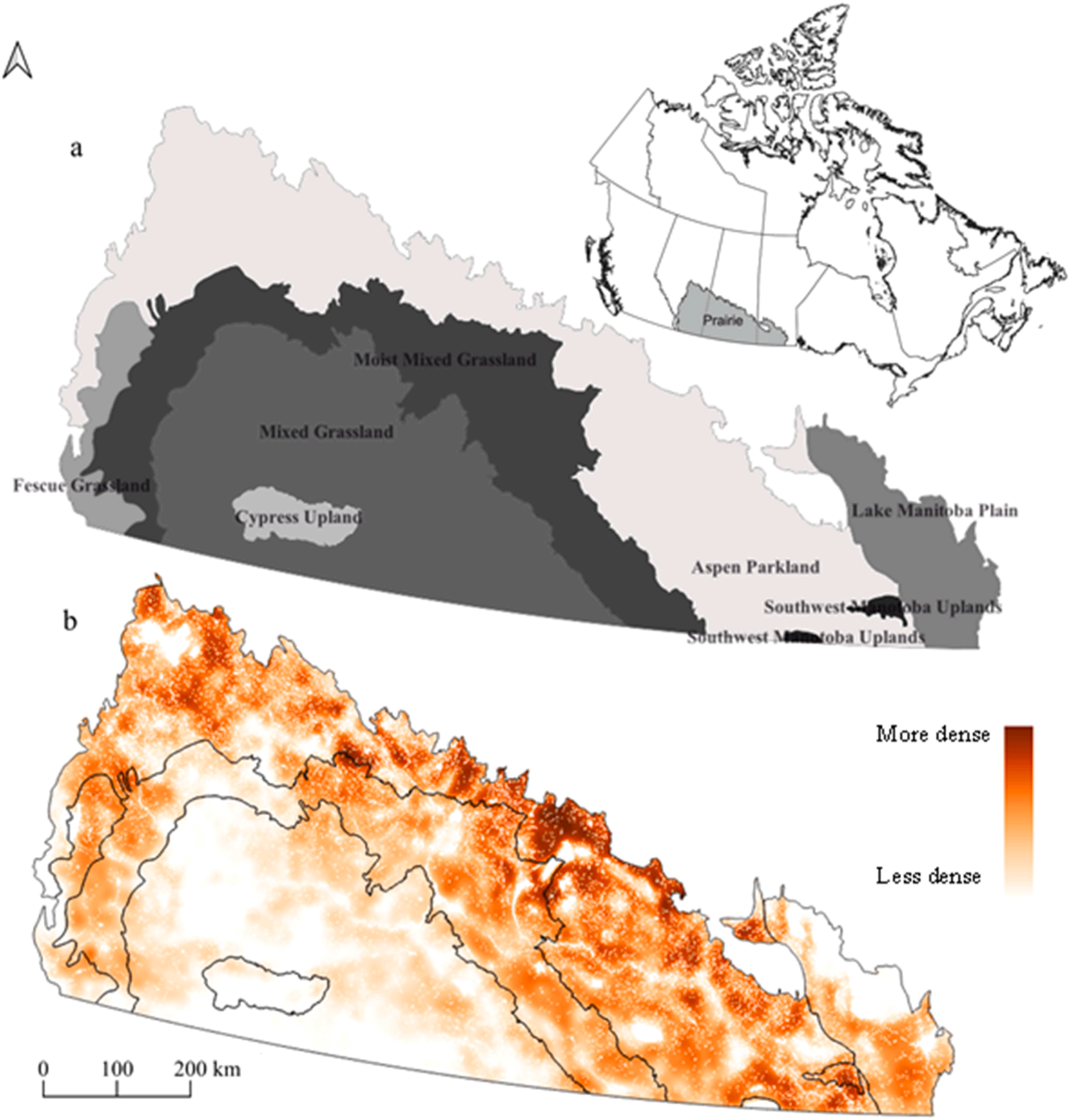

Fig. 1. The Canadian Prairie Region, where the simulations were run, is represented as the grey area on the map of Canada, (a) its ecoregions are represented in the zoomed-in region (Source: Agriculture and Agri-Food Canada, 2013) and (b) canola density in the Canadian Prairie Region. The darker the orange, the more canola production is cultivated (Source: Agriculture and Agri-Food Canada, 2023).

temperature of 16°C. The Mixed Grassland is a semiarid zone with mean summer temperatures of 16°C and total annual precipitation of approximately 300 mm. Crops tend to suffer from water deficits due to low precipitation and high evapotranspiration. The Moist Mixed Grassland has lower summer temperatures than the Mixed Grassland ecoregion but higher annual precipitation. Oilseeds are an increasing crop in this ecoregion. However, some irrigation may be needed under current conditions to improve production. Finally, the abiotic conditions of the Southwest Manitoba Uplands are similar to the Lake Manitoba Plain ecoregion, although it has slightly lower annual precipitation. Zones with lower elevation in this ecoregion have good conditions for crop production, including oilseeds, but some areas require drainage management (Agriculture and Agri-Food Canada, 1995). Canola cultivation is expected to mainly occur in the Aspen Parkland, Fescue Grassland, Moist Mixed Grassland and a part of Lake Manitoba Plain and of the Southwest Manitoba Uplands (Fig. 1) (Agriculture and Agri-Food Canada, 2023).

2.2. Crop model

In this study, canola growth and yield predictions were simulated in exclusively rainfed conditions using DSSAT CROPGRO-Canola (Jones et al., 2010). Each module and submodule operate subroutines (Table 1) to simulate the treatments introduced as input with biological (photosynthesis, phenological and root development, and yield formation), chemical (nutrient cycling, fertilizer application and transformation, and soil organic matter decomposition) and physical (soil water balance, evapotranspiration, radiation interception, and weather dynamics) processes and combinations. There are seven modules in DSSAT operation: the Individual Plant Growth, Land Unit, Main Program, Management Operations, Soil, Soil-Plant-Atmosphere, and Weather.

2.2.1. Model calibration

Spatial simulations based on grid points in a resolution of 0.25° by 0.25° were run with the DSSAT-Pythia gridded framework (Christopher Villalobos, 2024). Simulation scenarios included the hybrid canola cultivar InvigorL340PC® developed by BASF Agricultural Solutions (BASF Corporation, 2025). The calibration and validation of the crop model were conducted following the methodologies outlined by (Asgari et al., 2022b; Ahmed et al., 2020). While InVigor®5440 has been previously calibrated and widely applied in CSM-CROPGRO-Canola simulations, it is no longer commercially available in Canada (RealAgriculture, 2025). To ensure the relevance and applicability of the study, the current hybrid canola cultivar InvigorL340PC® was calibrated and incorporated into the model. This update aims to provide growers and stakeholders with timely and accurate projections. Genetic parameters for each hybrid were calibrated using the Generalized Likelihood Uncertainty Estimation (GLUE) and Genetic Coefficient Calculator (GENCALC) tools available in DSSAT. Calibration was based on observed data from the 2022 variety trials conducted in Langdon, North Dakota, by North Dakota State University (Langdon Research Extension Center, 2022), including measurements of Canopy Height (m), Anthesis Date (DAP), Grain Oil Content (%), Physiological Maturity (DAP), and Yield (kg ha^{-1}) (Figure S1). Model validation was subsequently performed using observed data from variety trials conducted between 2020 and 2024 in Langdon (Langdon Research Extension Center, 2023), and Conrad, Havre and Kalispell, MT in 2023 (Fordyce et al., 2023). The parameters used in the calibration and inclusion of this new canola hybrid to DSSAT are shown in Table 2 (Gavasso-Rita et al., 2025a).

The calibration and validation of InvigorL340PC® were analyzed with the Normalized Root Mean Square Error (NRMSE), Coefficient of determination (R^2), and the index of agreement (d) in the HydroErr Module in Python (Roberts and Williams, 2025). The NRMSE quantifies the average magnitude of deviation between model simulations and observed data. The R^2 indicates the proportion of variance in the observed data that can be explained by the model, reflecting the strength of the linear relationship between predicted and observed values (Kuhn and Johnson, 2013). The *d* evaluates the degree to which the simulated values correspond to the observed data, providing a standardized measure of model performance (Pontius Jr, 2022).

$$NRMSE = \frac{\left(\frac{1}{n}\sum_{i=0}^{n}(S_i - O_i)^2\right)^{\frac{1}{2}}}{\overline{O}} \tag{1}$$

$$R^2 = \frac{\left(\sum_{i=1}^{n}(O_i - \overline{O})(S_i - \overline{S})\right)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2 \sum_{i=1}^{n}(S_i - \overline{S})^2} \tag{2}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}\left(|S_i - \overline{O}| + |O_i - \overline{O}|\right)^2} \tag{3}$$

Where *O* is an array of observed data and *S* is an array of simulated data. These analyses are widely adopted by the scientific community (Asgari et al., 2022a). The calibration and validation of yield resulted in excellent model performance (NRMSE = 0.032, R^2 = 0.995 and d = 0.998) (Fig. 2).

Table 1
Summary of the Decision Support System for Agrotechnology Transfer main modules for canola production simulation (Source: Jones et al., 2010).

Module	Focus	Simulation
CROPGRO-Canola	Individual Plant Growth (process-oriented and mechanistic)	Simulates canola growth based on plant physiological and phenological responses to environmental forcing and mineral nutrition by following an agronomic approach based on daily weather and soil data and incorporating carbon assimilation and partitioning, besides pest and disease presence and effects
Management Operations	Planting and harvesting and all practices in between	Estimates and simulates planting and harvesting dates, and irrigation, fertilization and residue applications according to soil and weather conditions
Soil	Soil water and chemical balance (one-dimensional tipping bucket approach)	Computes soil dynamics, water, organic matter, inorganic nitrogen, and phosphorus and the soil water balance, besides structuring the soil characteristics by layers
Soil-Plant-Atmosphere	Soil-Plant-Atmosphere processes	Simulates evapotranspiration, water uptake, and soil temperature
Main Program	Module operations	Controls all the module operations, timing, and user input switches

Table 2
Parameters used for canola hybrid InVigor®-L340PC for calibration of phenology (P) and growth (G), or not used for calibration, only simulation (N).

Parameter	Use	Value	Definition
CSDL (hour)	P	16	Critical Short-Day Length below which reproductive development progresses with no daylength effect
PPSEN (1/hour)	N	−0.011	Slope of the relative response of development to photoperiod with time
EM-FL (PD*)	P	28.7	Time between plant emergence and flower appearance
FL-SH (PD)	P	12.7	Time between first flower and first pod
FL-SD (PD)	P	18.9	Time between first flower and first seed
SD-PM (PD)	P	25.76	Time between first seed and physiological maturity
FL-LF (PD)	P	2.09	Time between first flower and end of leaf expansion
LFMAX (mg CO_2/m^2-s)	N	1.28	Maximum leaf photosynthesis rate at 30°C, 350vpm CO_2, and high light
SLAVR (cm^2/g)	G	330	Specific leaf area of cultivar under standard growth conditions
SIZLF (cm^2)	G	100	Maximum size of full leaf
XFRT	N	2	Maximum fraction of daily growth that is partitioned to seed + shell
WTPSD (g)	N	0.002	Maximum weight per seed
SFDUR (PD)	G	20.8	Seed filling duration for pod cohort at standard growth conditions
SDPDV (number/pod)	G	22	Average seed per pod under standard growing conditions
PODUR (PD)	G	3.2	Time required for cultivar to reach final pod load under optimal condition
THRSH	N	95	The maximum ratio of *seed/(seed+shell)* at maturity
SDPRO	N	0.23	Fraction protein in seeds
SDLIP	N	0.48	Fraction oil in seeds

[*] PD = Photothermal Days

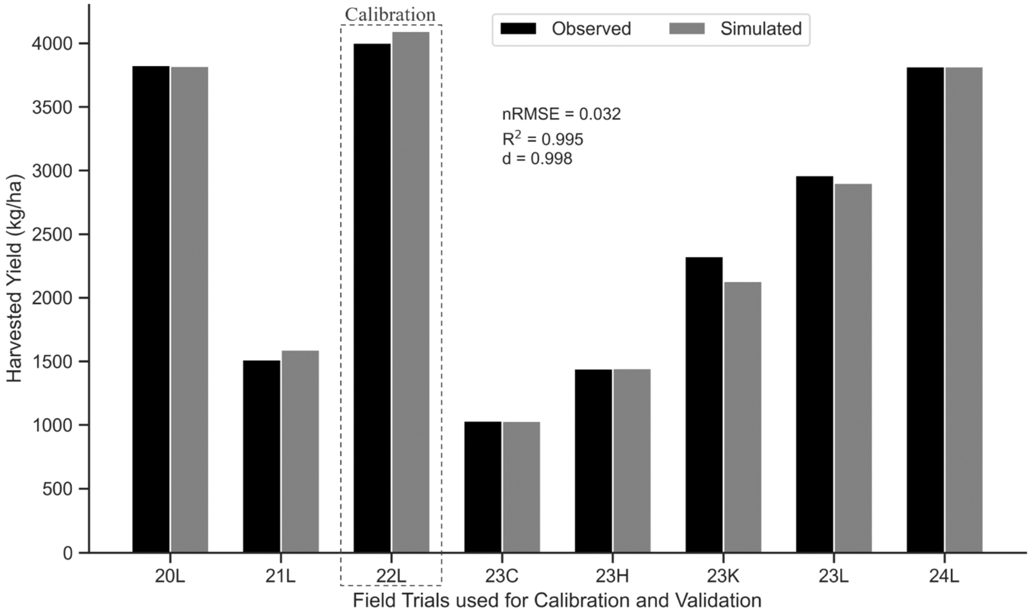

Fig. 2. The observed and simulated values of Yield (kg ha^{-1}) during calibration and validation of DSSAT CSM-CROPGRO-Canola for the canola hybrid InVigor®-L340PC in Conrad (C), Havre (H), Kalispell (K), and Langdon (L) from 2020 to 2024 (20−24).

The planting date input for the simulations was May 15, a common current date (Barthet, 2022), to avoid flower blasts or seedling losses in the Canadian Prairie Region (Bayer Crop Science Canada, 2025). Based on Gavasso-Rita et al. (2025a), application of 200 kg N ha^{-1} in the form of Ammonium sulfate was input to the Management Operations Module, 33 % at seeding and 67 % 30 days after planting, to ensure a higher nitrogen availability during vegetative stages (Jégo et al., 2022).

2.2.2. Climate change scenarios

To analyze future climate influence on canola production, downscaled daily weather data for historical and each SSP was used to create and ensemble from the following global climate models: ACCESS-CM2, ACCESS-ESM1–5, CanESM5, CMCC-ESM2, EC-Earth3, EC-Earth3-Veg-LR, GFDL-ESM4, INM-CM4–8, INM-CM5–0, and MPI-ESM1–2-LR (Figure S3), part of the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) see (O'Neill et al., 2016; Riahi et al., 2017), downscaled by the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) (Thrasher et al., 2022; Thrasher and Brosnan, 2024) with fine spatial resolution (0.25° by 0.25°). The weather files incorporated data on air temperature, precipitation, relative humidity, solar radiation, and wind speed, spanning historical records from 1990 and projections up to 2050. Canola responses were evaluated under both Current and Future climate scenarios (SSPs). The Current scenario utilized climate data from 2000 to 2020. Given that historical data from CMIP6 concludes in 2014, climate data for the period 2015–2020 was extrapolated from SSP2–4.5, as its trends align closely with historical patterns (O'Neill et al., 2016, 2017). Future climate projections based on SSP data were analyzed for the period 2025–2050 (Figure S4). The physical and chemical soil characteristics are from the SoilGrids™ database (10-km grid cell spatial resolution) (Han et al., 2019; IRI et al., 2018). SoilGrids™ developers estimate required soil parameters for DSSAT simulations and create global gridded soil profile datasets in DSSAT-specific format. Estimation methods and the generation of soil hydraulic properties are described in Han et al. (2019). Estimated soil moisture characteristics include saturated hydraulic conductivity, soil water content at field capacity, wilting point, and saturation per layer (Han et al., 2019; IRI et al., 2018).

2.2.3. Soil water content simulation

Soil water content metrics for future seasons of canola production were simulated in DSSAT Soil Module and SPAM (Jones et al., 2010) combined with DSSAT-Pythia from 2025 to 2050. Soil water evaporation was calculated in DSSAT based on Ritchie et al. (2009). The processes included in the soil water balance calculation are the soil evaporation, crop transpiration, runoff, infiltration of rainfall and irrigation, drainage of profile and below root zone, and distribution of root water uptake from soil layers (Boote et al., 2008). We also selected the Penman-Monteith method from the Food and Agriculture Organization of the United Nations (FAO) (Allen et al., 1998) to calculate reference evapotranspiration. The chosen evaporation and evapotranspiration methods were included in the fourth version of DSSAT (Thorp et al., 2020). Separate calculations of soil water evaporation occurred before canola planting date in the simulation. After canola is planted, the reference evapotranspiration was then combined with the crop coefficient from CROPGRO-Canola to base potential and crop evapotranspiration (Thorp et al., 2020). The weather input files with air temperature, precipitation, relative humidity, solar radiation, and wind speed data were used in the calculations. A detailed description of the processes related to water balance in DSSAT CROPGRO can be found in Boote et al. (2008).

2.2.4. Water and temperature stress factors

DSSAT simulated two water stress factors for each future climate scenario to serve as regulatory signals for crop processes. The water stress factors focus on photosynthesis and growth processes. In the plant turgor factor (WSFGrowth), the water stress reduces the expansive processes (growth) before the photosynthesis process is impacted. In the soil water stress factor (WSFPhotos), the water stress is applied on the stomatal conductance as a reduction factor leading to both transpiration and photosynthesis decline. Both factors consider the ratio of potential root water uptake to the potential plant transpiration and are limited to 1.0 (maximum). When WSFGrowth and WSFPhotos are below 1, water stress may reduce canola canopy cover, leaf expansion, biomass accumulation, potential root depth, potential canola growth, and yield and accelerate leaf senescence and nitrogen mobilization during the grain-filling stage (Boote et al., 2008; Hoogenboom, 2019a; Hoogenboom et al., 2019b).

$$\text{WSFGrowth} = \frac{\textit{Total potential root water uptake}}{((ET_0 \text{ x } [1.0 \ - \exp(-KEP \text{ x } LAI)] \text{ x } 1.5)} \tag{4}$$

$$\text{WSFPhotos} = \frac{\textit{Total potential root water uptake}}{(ET_0 \text{ x } [1.0 \; - \exp(-KEP \text{ x } LAI)]} \tag{5}$$

Where, ET_0 is potential evapotranspiration, KEP is total solar energy extinction coefficient, and LAI is leaf area index. DSSAT uses cardinal temperatures to simulate developmental and growth processes. Maximum and minimum daily air temperature data are used to simulate canola growth. Reproductive growth only occurs when air temperature is above canola base temperature. The temperature impact on canola growth is calculated daily (Porter et al., 1999).

$$\text{PT} = \quad 1 - 0.0025((0.25TMIN + 0.75TMAX) - 26)^2 \tag{6}$$

Where PT is growth rate reduction factor, TMIN is minimum daily temperature, and TMAX is maximum daily temperature. Canola's potential growth rate is limited by water through WSFPhotos and temperature through PT. These factors affect leaf number increase and leaf area index during the vegetative phase. During the reproductive phase, GDD accumulation alters the maturity rate (Porter et al., 1999).

3. Results

3.1. Projected changes in soil water content and air temperature

Simulated average daily soil water content for all future SSP climate scenarios, mean daily maximum and minimum air temperatures occurring during the growing seasons are shown in Fig. 3. Results show that the Northwestern part of Aspen Parkland has reduced soil water content mainly under SSP3–7.0 and SSP5–8.5 scenarios than current, with average minimum and maximum daily values around 0.19 and 0.20 cm^3 cm^{-3}, respectively, in the first 60 cm of soil depth. This represents a reduction from current conditions between 0.0020 and 0.0009 cm^3 cm^{-3}. The Moist Mixed Grassland resulted in higher soil water content values than the Cypress Upland, Mixed Grassland, and Southwest Manitoba Uplands Ecoregions but lower values than the other ecoregions ($<$ 0.16 cm^3 cm^{-3}). SSP2–4.5 and SSP5–8.5 simulations suggest the highest values of soil water content in Southern Alberta, and the extreme South of Saskatchewan and Manitoba closer to Aspen Parkland (+0.0065 cm^3 cm^{-3}, on average) over current conditions. The western part of the Prairie Region, which encompasses Fescue Grassland and part of Aspen Parkland, shows higher values of future soil water content under SSP1–2.6 (+0.0030 cm^3 cm^{-3}, on average) and SSP2–4.5 (+0.0040 cm^3 cm^{-3}, on average), and low to no difference under SSP3–7.0 and SSP5–8.5 scenarios (+0.0005 cm^3 cm^{-3}, on average).

Maximum air temperatures increase across all climate scenarios to varying degrees (Fig. 3). SSP5–8.5 predicts changes in higher maximum air temperatures of + 1.5°C on average in all ecoregions during the growing season from 2025 to 2050. Lowest maximum (20°C) and minimum (5°C) air temperatures are expected to occur west of the Prairie Region (i.e., in Fescue Grassland and Aspen Parkland ecoregions). As might be expected, these regions have higher soil water content (0.24 cm^3 cm^{-3}, on average) across all SSPs. This is influenced by the Bowen ratio as higher soil moistures lead to lower Bowen ratios due to higher allocation of net radiation to latent heat, reducing sensible heat and thus surface temperature (Jin and Mullens, 2014; Oliver and Ratio, 2005). Additionally, lower air temperatures decrease the air's moisture-holding capacity, leading to reduced evaporation rates (Cengel et al., 2023). Conversely, higher air temperatures can elevate surface temperatures, enhance evaporation, and consequently result in drier soils (Cengel et al., 2023). Therefore, regions with drier conditions are expected to experience higher surface temperatures during the growing season. The average daily temperature amplitude during the growing season is higher in the southern areas of the Prairie Region, with the highest amplitude (18°C) expected in the Mixed Grassland, Cypress Upland and the western part of the Fescue Grassland and Moist Mixed Grassland across all SSPs. The lowest temperature amplitude (10°C) is expected to occur in Aspen Parkland in Manitoba under SSP1–2.6 and SSP3–7.0. This area is expected to have less temperature variability in the whole region.

3.2. Projected water stress under SSPs

Under WSFPhotos stress conditions, the DSSAT model simulates enhanced root growth, allowing roots to extend into deeper soil layers. Concurrently, the model predicts accelerated leaf senescence and grain filling processes, resulting in grains with reduced content. WSFGrowth limits vegetative expansion in DSSAT, decreasing the leaf area index and stem elongation. Our results show that canola vegetative expansion and photosynthesis performance were affected by water deficit in all ecoregions under all SSPs in June and July, with greatest impacts under SSP5–8.5 (Fig. 4). Simulations resulted in both water stress factors expected in June under SSP1–2.6, SSP2–4.5 and SSP3–7.0, and in June and July under SSP5–8.5. As expected, the highest values for both water stress factors occurred in the Cypress Upland and Mixed Grassland

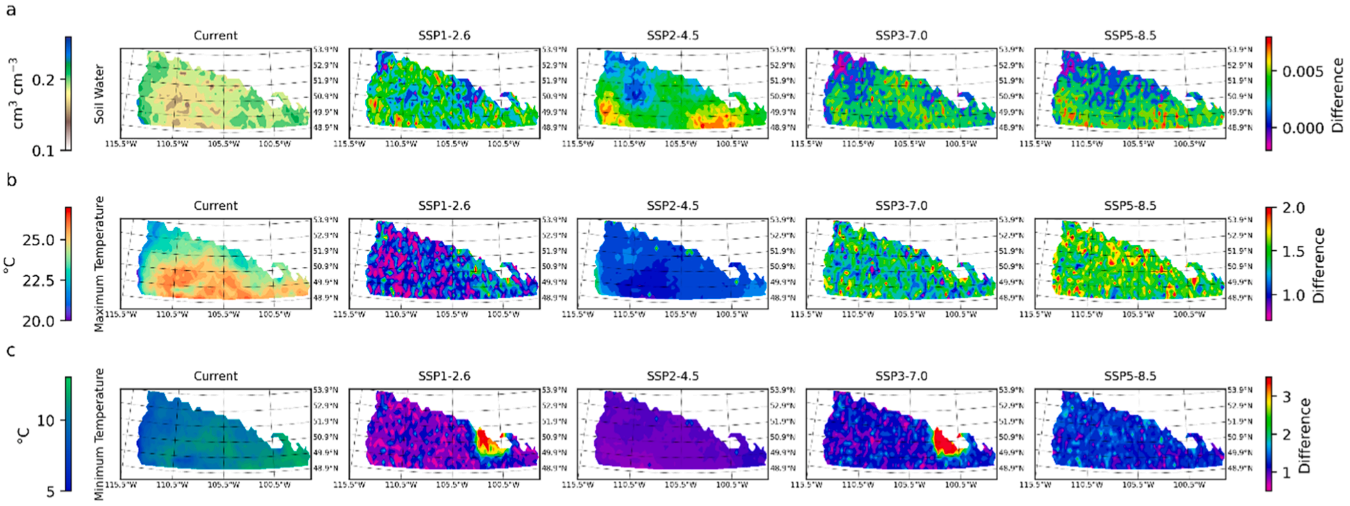

Fig. 3. Spatial distribution of key agroclimatic variables during the growing season (May–September) averaged over 2025–2050: (a) simulated daily average soil water content (cm^3 cm^{-3}) in the top 60 cm of soil, (b) maximum value of the mean daily maximum air temperature (°C), and (c) minimum value of the mean daily minimum air temperature (°C). All variables are shown under the current scenario, along with their differences relative to SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 climate scenarios.

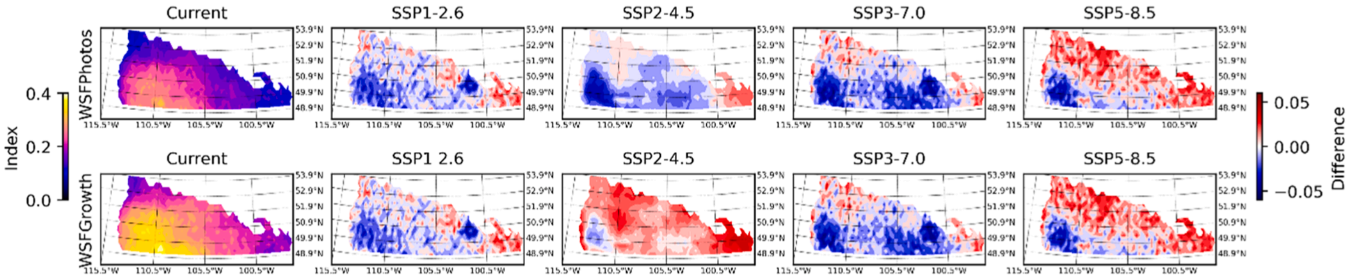

Fig. 4. Map of the average water stress factors WSFPhotos and WSFGrowth during the growing season simulated for canola production, where 0 means no water stress and 1 means high water stress in the Canadian Prairie Region shown under the current scenario, along with their differences relative to SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 climate scenarios.

ecoregions (0.3, on average) across all climate scenarios. Canola photosynthesis performance was affected by WSFPhotos across all ecoregions and SSPs. Lower impacts were found in the Northwestern area of Aspen Parkland and the Southeastern region of Lake Manitoba Plain in the Current scenario. An increase in both water stress factors is expected in the Southeastern region of Lake Manitoba Plain across all SSPs (+0.040, on average). All ecoregions of Saskatchewan and Manitoba are expected to suffer from WSFGrowth under SSP2–4.5 and increase by 0.025, on average, compared to the Current scenario. The exception is the extreme south (border of the Mixed Grassland and Moist Mixed Grassland), where the difference is close to zero. Canola production is less likely to suffer from water stress in Southern Alberta and Saskatchewan under SSP1–2.6 and SSP3–7.0. Simulated canola production suffered less (-0.030, on average) from WSFPhotos under SSP2–4.5 compared to Current scenario in most ecoregions in Alberta and Saskatchewan.

3.3. *Projected accumulated monthly growing degree days*

Generally, the higher the temperature, the more vegetative growth canola has, respecting temperature tolerance limits (Grains Research and Development Corporation, 2018). Fig. 5 represents the average monthly accumulated GDD (base 5°C) from May to September for all the climate scenarios. Given that emergence may last four to 15 Days After Planting (DAP) (Canola Council of Canada, 2024) and requires 0°C to 142°C accumulated GDD (North Dakota State University, 2025), accumulated GDD above that may accelerate the process. Simulated average monthly accumulated Growing Degree Days (GDD) post-May 15 indicate that emergence in the eastern Aspen Parkland of Saskatchewan and Manitoba will be supported under SSP1–2.6 and SSP3–7.0 scenarios (darker areas of the map in Fig. 5). In contrast, other regions are projected to experience accelerated development compared to the Current scenario under SSP1–2.6 and SSP3–7.0, as well as across all regions under SSP2–4.5 and SSP5–8.5.

Flowering and podding are crucial stages to set canola yield potential. The average simulated anthesis date was July 20 under the future climate scenarios. The flowering and podding until seed maturation stages can last from two to three weeks and 25–45 in ideal conditions, respectively (Canola Council of Canada, 2024). During three weeks after average anthesis day, average monthly accumulated GDD peaked at a slightly less than 210°C under SSP1–2.6 and SSP3–7.0, at 217°C under SSP2–4.5 and 220°C under SSP5–8.5 (Figure S5). Under ideal conditions, canola requires accumulated GDD of 519°C to 647°C during early flower stage and 648°C to 776°C during podding and seed maturation (North Dakota State University, 2025). On average, our results show an accumulation of 625.5°C during early flower stage and 859.5°C during podding and seed maturation, however hotter sites in Mixed Grassland and Cypress Uplands in Saskatchewan accumulated a maximum of

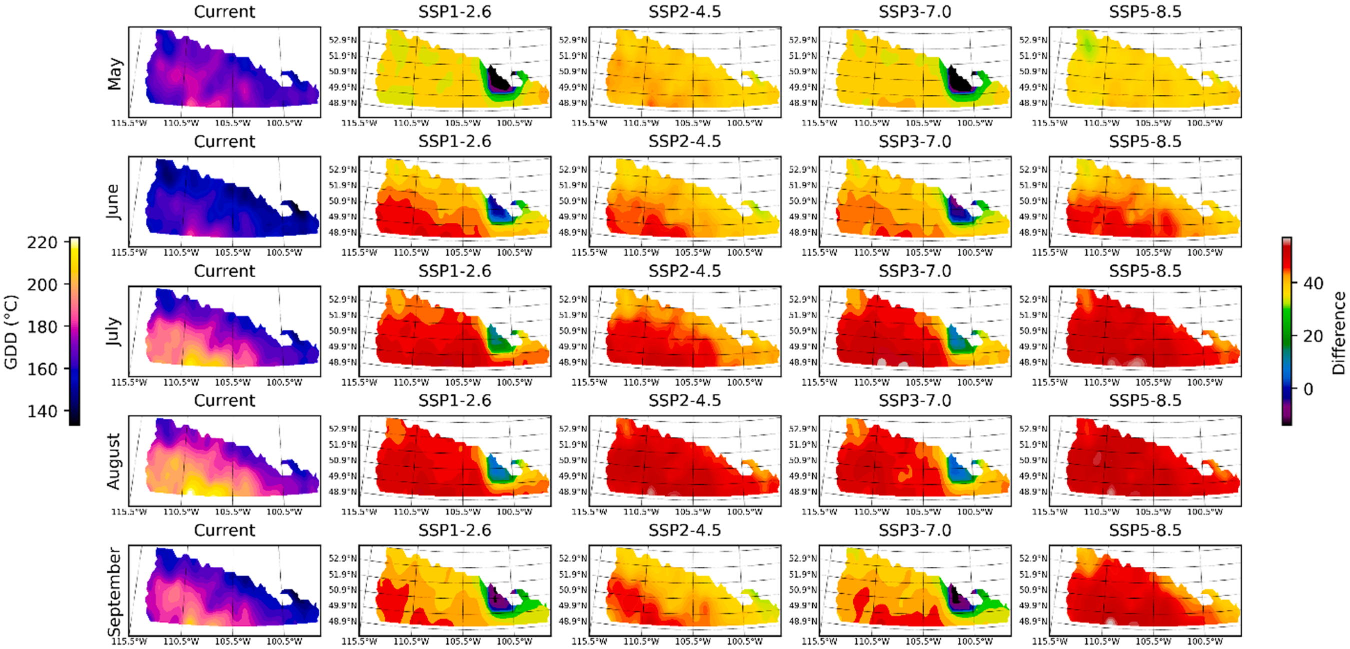

Fig. 5. Spatial distribution of the average monthly accumulated Growing Degree Days (GDD; °C) base 5°C from May to September shown under the current scenario, along with their differences relative to SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 climate scenarios.

732°C and 1011°C during these stages, respectively, with higher accumulation predicted under SSP2–4.5 and SSP5–8.5. This high accumulation of GDD shows that air temperatures were higher than ideal. Heat stress happening after bolting can reduce grain yield (Canola Council of Canada, 2024) (Fig. 6) with lower yield values predicted when higher air temperatures occur.

3.4. Joint effects of soil moisture and air temperature on canola yield

Simulated yield results for all climate scenarios are shown in Fig. 6. Average yield (kg ha^{-1}), maximum yield (kg ha^{-1}), mean daily soil water content (cm^3 cm^{-3}) in the first 60 cm of soil depth during the growing season, and mean daily air temperature (°C) during the growing season across climate scenarios, ecoregions, and provinces are summarized in Table S1. Yield values varied in response to the air temperature ranges across different climate scenarios, while soil water content remained consistent across all scenarios. The lowest yield values ($<$500 kg ha^{-1}) are mainly associated with air temperatures above 25°C and soil water content below 0.20 cm^3 cm^{-3} under SSP1–2.6. Yield values $<$ 800 kg ha^{-1} are associated with soil water contents under 0.17 cm^3 cm^{-3} and air temperatures above 24°C under SSP5–8.5. Most yield values above 2000 kg ha^{-1} were simulated when mean air temperatures during the growing season are between 21°C and 24°C and soil water content is between 0.16 and 0.19 cm^3 cm^{-3}. The average yield value (~1000 kg ha^{-1}) in Aspen Parkland occurs at a slightly higher air temperature under SSP5–8.5 than the other scenarios. In Cypress Upland, most simulations resulted in canola yield values under 26°C under SSP1–2.6 and SSP2–4.5 and at 26°C under SSP3–7.0 and SSP5–8.5. The lowest average yield value (~300 kg ha^{-1}) was simulated in Cypress Upland, the ecoregion with the most yield values in a rainfed production system with less than 0.90 cm^3 cm^{-3} of soil water content in all SSPs. Mixed Grassland is the ecoregion presenting the second lowest average yield value (~350 kg ha^{-1}), with most values occurring above 27°C and below 0.95 cm^3 cm^{-3}. Southwest Manitoba Uplands was the ecoregion with the highest average value of canola yield (~1050 kg ha^{-1}). Most of its production happened between 25°C and 26°C and under 1.05 cm^3 cm^{-3} of soil water content in this ecoregion, with the highest air temperature occurring under SSP5–8.5.

3.5. Projected yield spatial distribution across ecoregions

The map of simulated canola yield under different climate scenarios shows that there are areas of the Canadian Prairie Region where lower soil water content and higher air temperatures during future growing seasons will result in lower yield values and lower occurrence of yield (Fig. 7). This is especially the case for Cypress Upland and Mixed Grassland ecoregions, where predicted yield values will be mostly below 500 kg ha^{-1}. Lowest canola yields are expected to occur below 51° latitude in southeast Alberta and southwest Saskatchewan under the current scenario. Under SSP5–8.5, lowest yields extend northwards, in Aspen Parkland Ecoregion. Lower yield values (-250, on average) are expected in Manitoba across all SSPs compared to the Current scenario. Yields over 2000 kg ha^{-1} under a rainfed system are only expected to occur in the Aspen Parkland ecoregion (all SSPs) and Lake Manitoba Plain (SSP2–4.5), albeit at a much lower frequency than the current context. A key finding is that, under SSP5–8.5, average yields in Lake Manitoba Plain and Aspen Parkland in Saskatchewan decline by 203 ± 4.3 and 121 ± 13.6 kg ha^{-1} per growing season by 2050 respectively,

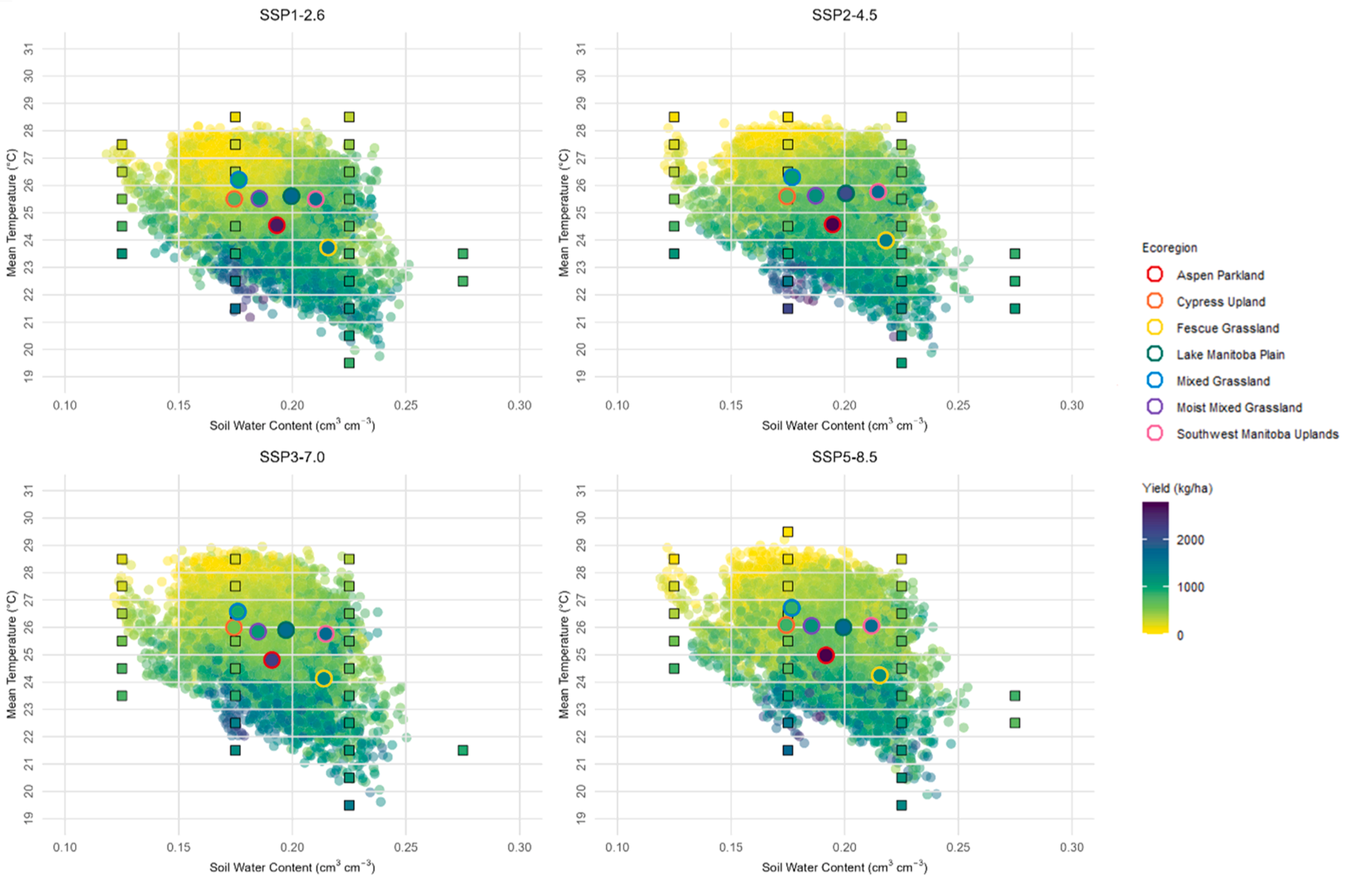

Fig. 6. Yield (kg ha^{-1}) distribution over the ranges of average daily air temperature (°C) during the growing season and daily average soil water content (cm^3 cm^{-3}) in the first 60 cm of soil depth during the growing season under SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5. The mean values of each range are represented in a square over the grid. Circles show where most of the values are characterized per ecoregion. Circle filings show the maximum yield value per ecoregion.

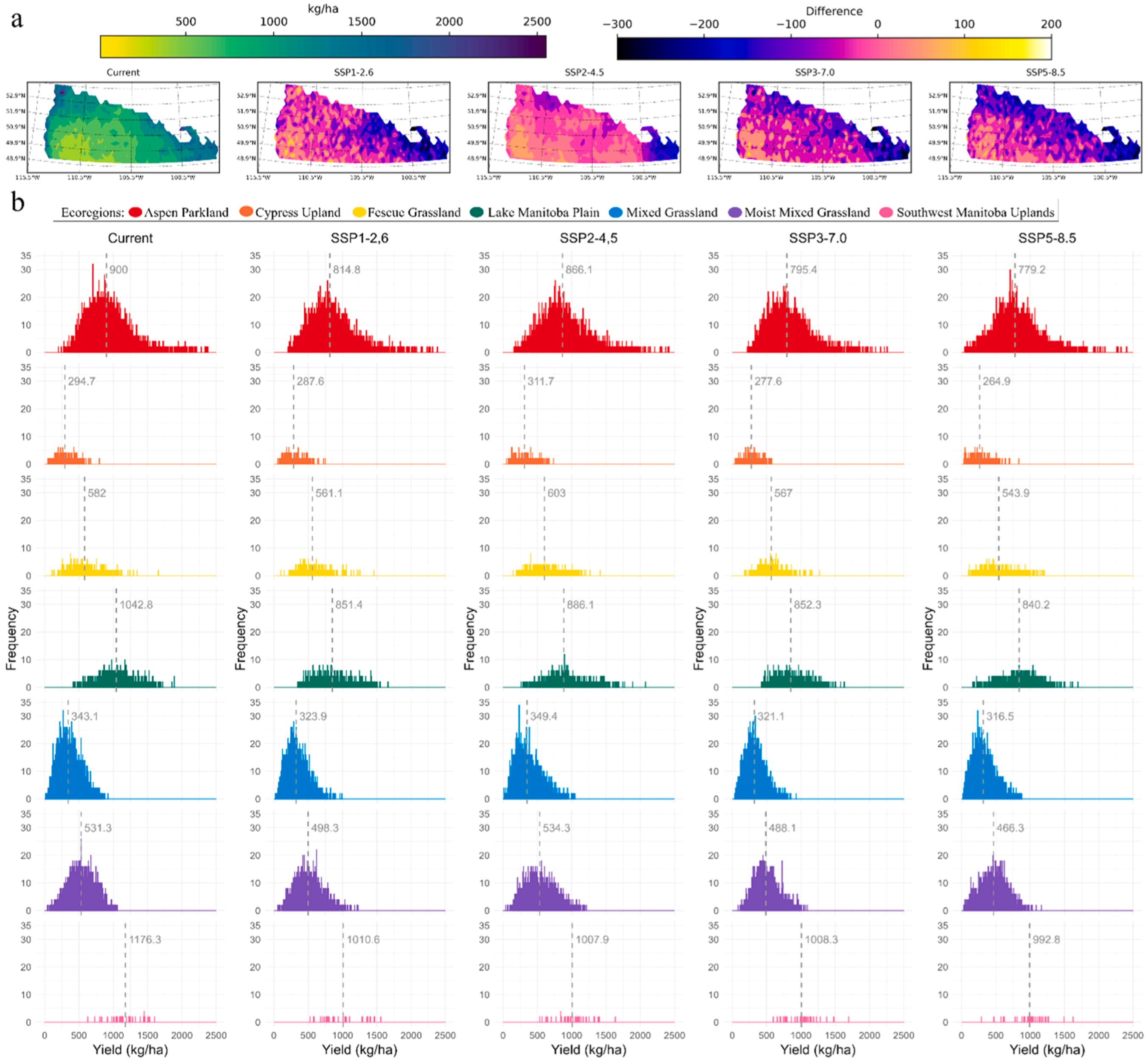

Fig. 7. Spatial distribution of (a) simulated canola yield (kg ha^{-1}) in temporal average (years) shown under the current scenario, along with their differences relative to SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 climate scenarios, and (b) frequency of the simulated canola yield in each ecoregion of the Canadian Prairie Region under Current, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 climate scenarios.

compared to the Current scenario. Aspen Parkland currently produces the majority of canola in the Prairie Region (Statistics Canada, 2025a).

4. Discussion

Air temperature has direct and indirect effects on canola health and productivity. When GGD accumulates faster during flowering and podding until seed maturation, usually when air temperatures are above 32ºC, it may accelerate maturity, promoting faster reproduction and grain filling, resulting in less grain content (Grains Research and Development Corporation, 2018). Overall in reproductive stages, heat stress may impact pollen viability, causing pollen abortion and low pod fertility, besides altering the seed appearance, weight, size, and content (Lohani et al., 2022; Wu et al., 2021b). Canola might also present abnormal floral organs from high air temperatures and water deficit (Kourani et al., 2022). Indirectly, elevated temperatures boost evaporative losses due to increases in vapor pressure deficit, leading to soil water deficit (Cui et al., 2022). However, effects on crop phenology depend on canola's developmental stages (Boote et al., 2008). In reality, canola germination highly depends on water availability as the seeds need to absorb water to activate the biochemical processes to emerge the roots and cotyledons (Canola Council of Canada, 2024; Bayer Crop Science Canada, 2021). Negative impacts on vegetative growth also affect photosynthesis, mainly because the leaf area index can be reduced, decreasing the exposure area of the leaves to solar radiation and, consequently, accumulating less dry matter (Canola Council of Canada, 2024). Higher temperatures are expected to accelerate vegetative growth and boost photosynthesis. However, it reduces stomatal conductance and photosynthesis when combined with water stress as the plant simultaneously tries to avoid overheating and water loss (Kourani et al., 2022). At the field, the flowering and podding stages are susceptible to the combination of heat and water stresses. The carbon assimilation by the photosynthesis process regulates grain oil accumulation. Hence, if water stress occurs during the grain filling stage and photosynthesis performance is reduced, the grain oil content is negatively impacted.

Short-period combined stress may reduce canola yield by more than 10 % and 30 %, respectively (Secchi et al., 2023). Still, the average canola yield for 2024 was 1816, 1883, and 1816 kg ha^{-1} in Alberta, Manitoba, and Saskatchewan, respectively (Statistics Canada, 2025a). These include both irrigated and rainfed production systems. Our results show that reaching these values in an exclusively rainfed production system in the future is achievable in Aspen Parkland, Lake Manitoba Plain and Southwest Manitoba Uplands ecoregions. Regardless of the climate scenario, current ecoregions where canola is currently grown are expected to be able to produce higher yields. Despite a general increase in yields, results show that under SSP5–8.5, average yields in Lake Manitoba Plain and Aspen Parkland in Saskatchewan decline by 203 ± 4.3 and 121 ± 13.6 kg ha^{-1}, respectively. Hence, adaptation to the effects of a changing climate is necessary to minimize negative impacts on canola yield and grain quality. A study exploring canola producer experiences with a changing climate in the Prairies (Gavasso-Rita et al., 2025b) showed that more than 50 % of the producers faced decreased soil moisture and water shortages and reported large losses in canola growth and yield in Manitoba due to short-period droughts and large losses in Saskatchewan from prolonged droughts. In addition, approximately 50 % experienced large losses in canola growth and yield from heat waves. These canola producers consider changing planting dates, planting diversified crops, using reduced or no tillage, restoring or preserving wetlands, and using a fertilization plan as the most viable adaptation strategies (Gavasso-Rita et al., 2025b).

Choosing and planting seeds with high tolerance to abiotic effects and changing planting dates and fertilization plans are great adaptation strategies and work well in the Prairie Region (Gavasso-Rita et al., 2025a; Jégo et al., 2022; Nelson et al., 2022; de Oliveira et al., 2024; Wen et al., 2021, 2023). Adapting to an early planting date may extend the growing season, alleviating the negative effects from higher air temperatures and water availability (Gavasso-Rita et al., 2025a). Conservation tillage, subsoiling or no tillage in regions with rainfall variability and uneven rainfall distribution regulates water availability, helping improve water use efficiency and increase yield (Zhang et al., 2022). In addition, the water retention capacity of the soil can be improved from 20 % to 132.2 % with biochar application, depending on the biochar's straw (Huang et al., 2024). Furthermore, implementing irrigation to meet canola potential demands may benefit canola productivity, increasing yield and local economy. However, irrigation expansion without proper planning, water allocation, frequency and meeting the drainage requirements may impact surface and groundwater water quality, especially from field runoff and by the altering the water-energy balance from increased evapotranspiration (Canada, 2025; Zaerpour et al., 2024). The potential expansion of water demand in the Canadian Prairie Region due to changes in climate may also induce updates to the Master Agreement on Apportionment, a transboundary water agreement among the federal government and the Prairie Provinces, to ensure that Saskatchewan and Manitoba are allocated sufficient water for consumption (Canada, 2025).

Mitigation is also essential to avoid global warming. The SSP5–8.5 represent the least optimistic narrative of the future. This scenario narrates fast technological and human capital progress, which reflects high challenges to mitigation, mainly because of the heavy exploitation of fossil fuel resources (O'Neill et al., 2017). It also represented the greatest reduction in yield values relative to the Current scenario. Renewable energy is a sustainable solution to environmental conservation as it helps mitigate greenhouse gas (GHG) effects by reducing CO_2 emissions. It also raises the opportunity for reconciliation by implementing and developing renewable energy projects in Indigenous communities guided by Indigenous leaders (Hoicka et al., 2021). Although Canada has been facing environmental problems, the country has diversified energy sources and reduced fossil fuel usage by incorporating and increasing renewable energy consumption (Adebayo, 2022). Canadians highly support biofuels, and most supporters are aware of climate change and the environmental impacts of GHGs. They expect biofuel usage to reduce emissions (Dragojlovic and Einsiedel, 2015). Canadian urbanization is connected to its economic growth, trade, and increased CO_2 emissions, which motivates renewable energy use (Rahman and Vu, 2020). Oilseeds are a great alternative feedstock for biofuel production in Canada (Blackshaw et al., 2011), and canola is currently the dominant feedstock for biodiesel generation, producing clean energy (Wu et al., 2021a). Hence, adapting canola production to improve its tolerance to abiotic factors may help the mitigation process, reducing the negative impacts on canola production.

Despite findings, there are some limitations to the current study. The availability of field measurements for the newly released canola cultivar was limited. The calibration focused on physiological parameters most strongly associated with canopy development and water use efficiency. Parameters linked to leaf area index (LAI) and actual evapotranspiration (Eta) were prioritized to capture the cultivar's growth dynamics and yield response under varying environmental conditions. Previous studies have demonstrated close relationships among LAI, ETa, phenology, and yield components such as plant height and oil accumulation under water or temperature stress (Gan et al., 2011; Ghaffari et al., 2023; Katuwal et al., 2020; Song et al., 2019). Acknowledging this limitation provides a foundation for refining methodologies in subsequent studies.

5. Conclusion

Combined impacts of air temperature and soil water content on spring canola production in the Canadian Prairie Region under diverse climate scenarios by 2050 are expected in a rainfed system. Canola's main growing zone in Aspen Parkland is expected to experience higher air temperatures and lower soil water content. An average increase of 1.5°C in air temperature and 0.025 in the water stress factor indices may result in yield reductions of approximately 203 ± 4.3 and 121 ± 13.6 kg ha^{-1}, in Lake Manitoba Plain and Aspen Parkland ecoregion (mainly in Saskatchewan) per growing season, respectively.

When analyzing simulated future water stress during the growing season and exploring the joint effect of soil water content and air temperature on rainfed spring canola production, water deficit is expected to impact canola growth, photosynthesis performance, and vegetative expansion, altering diverse biochemical and physiological processes and harming productivity, especially under SSP5–8.5. Water stress is expected to be more severe in Manitoba, especially under SSP2–4.5. Heat stress is also expected to worsen by 2050, and the combination of heat stress with water deficit may reduce canola yields by up to 20 % over current yields. Adaptation to the new climates is necessary to prevent large yield losses. Additional cropland conversion is not seen as a good mitigation strategy, as Cypress Upland and the southern area of the Mixed Grassland ecoregions are the least suitable for cultivating canola. Highest yields are predicted to continue to occur in current high yield regions of Aspen Parkland, Lake Manitoba Plain and Southwest Manitoba Uplands.

CRediT authorship contribution statement

Yohanne Larissa Gavasso-Rita: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Masoud Zaerpour:** Writing – review & editing, Visualization, Conceptualization. **Simon Michael Papalexiou:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Corinne Schuster-Wallace:** Writing – review & editing. **Athanasios Paschalis:** Writing – review & editing. **Yanping Li:** Writing – review & editing, Supervision, Funding acquisition. **Amin Elshorbagy:** Writing – review

& editing. **Hebatallah Abdelmoaty:** Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2025.109966.

Data availability

Data will be made available on request.

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